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Saturn's tropospheric particles phase function and spatial distribution from Cassini ISS 2010–11 observations

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ABSTRACT

The phase function describes the way particles scatter the incoming radiation. This is a fundamental piece of knowledge in order to understand how a planetary atmosphere scatters sunlight and so it has a profound influence in the retrieved atmospheric properties such as cloud height, particle density distribution and radiative forcing by aerosols. In this work we analyze data from the Imaging Science Subsystem (ISS) instrument onboard Cassini spacecraft to determine the particle phase function at blue (451 nm) and near infrared wavelengths (727–890 nm) of particles in the upper troposphere, where most of the incoming visible sunlight is scattered. In order to do so, we use observations taken in later 2010 and 2011 covering a broad range of phase angles from ∼10° to ∼160° in the blue (BL1) and near infrared filters associated with intermediate and deep methane absorption bands (MT2, CB2, MT3). Particles at all latitudes are found to be strongly forward scattering. The equatorial particles are in good agreement with laboratory measurements of 10 μm ammonia ice crystals, while mid- and sub-polar latitude particles may be similar to the equatorial particles, but they may also be consistent with 1 μm ellipsoids with moderate aspect ratios. Uncertainties due to limited phase coverage and parameter degeneracy prevent strong constraints of the particle shapes and sizes at these locations. Results for the particle phase function are also used to describe the spatial distribution of tropospheric particles both vertically and latitudinally in the Northern hemisphere.

1. Introduction

The distribution of aerosols and particles in the upper troposphere and lower stratosphere of the giant planets is a fundamental piece of information in order to understand the way the atmospheres of these bodies behave. Aerosols act both as scatterers and as absorbers and both roles are essential. By reflecting the incoming sunlight, they serve as tracers for the atmospheric dynamics. These tracers allow the determination of the zonal wind profile (García-Melendo et al., 2011; Vasavada, 2006) and its local features (García-Melendo et al., 2010). They also reveal the presence of particular atmospheric structures (del Río-Gaztelurrutia et al., 2010), the most obvious ones being the periodic giant storms (often nicknamed Great White Spots, GWS hereafter) arising roughly every seasonal cycle, as seen in 1990 (Sánchez et al., 1993; Sánchez-Lavega et al., 1991) and 2010 (Fischer, 2011; Sánchez-Lavega, 2011a; Sánchez-Lavega et al., 2012; Sayanagi et al., 2013). But aerosols forming cloud features do not just serve as passive tracers for the atmospheric dynamics, the combination of their absorption and scattering also has an influence in the energy budget of the planet as reviewed in Pérez-Hoyos and Sánchez-Lavega (2006b). Thus, the goal of this paper is to provide a better understanding of how the saturnian tropospheric aerosols scatter and absorb solar radiation at visual wavelengths.

Briefly speaking, the evolution of our understanding of this topic (i.e. retrieval of vertical distribution of Saturn's upper tropospheric/lower stratospheric particles by means of reflected sunlight at visible wavelengths) is profoundly influenced by the advances in the spacecraft exploring Saturn and their particular orbits. The state of the art by the early 1980s is summarized by the work of Tomasko et al. (1984), in particular the use of methane bands in the near infrared for sounding the planet's atmosphere (West, 1983). Data from Pioneer 11's 1979 flyby of Saturn had

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provided our first opportunity for measuring the scattering phase function of aerosols in Saturn's atmosphere (Tomasko and Doose, 1984; 1985) at blue (∼440 nm) and red wavelengths (∼640 nm). The years after the launch of the Hubble Space Telescope provided additional information on general atmospheric properties (Karkoschka and Tomasko, 2005; Pérez-Hoyos et al., 2005) while other ground-based observatories (Temma et al., 2005) contributed to the topic. This, together with early work by the Cassini mission, was compiled by West et al. (2009). During the Cassini era, the most notable work on this topic is the study of Roman et al. (2013), which is based in a set of observations very similar to the ones used in this research, although taken some seven years earlier and restricted in phase angle coverage. Obviously, particle properties and related phenomena can also be studied at other wavelengths, e.g. the emitted thermal radiation as in West et al. (2009) or Fletcher (2011), Fletcher et al. (2011), but, all in all, if we want to understand the atmospheric regime as a whole we need to have a good information on where in the atmosphere the particles acting as tracers are located.

In spite of the advancement during the last 30 years, particularly due to the use of longer wavelengths to sound levels deeper and higher in the atmosphere than those sounded in the visible, the phase function used to describe the way the particles in the upper troposphere scatter incoming radiation is still the one determined by Tomasko and Doose (1984). The prevalence of the Pioneer's phase function is mainly due to the impossibility of observing Saturn at phase angles greater than 6° from Earth. The phase angle is defined as the observer–Saturn–Sun angle and supplements the scattering angle. Thus, ground-based observations limited to low phase angles provide information mostly on the backscattering, while access to the forward scattering requires observations at high phase angles only attainable from spacecraft in orbit around the planet. Since the flybys in the early 1980s, no spacecraft has provided access to this information. During Saturn's seasonal cycle, the characteristic size or shape of the tropospheric particles could have been substantially changed thus modifying the particle phase function. This could in turn result in less accurate vertical cloud structure models and hence, the main goal of this paper is to constrain the particle phase function at least for a snapshot covering Saturn's Northern hemisphere during late 2010 and during 2011, comparing it with the early work based on Pioneer 11 photometry (Tomasko and Doose, 1984) in 1979. It must be noted that the Pioneer data were restricted to two broad bands, while Cassini ISS allows the use of narrow filters around methane bands which provide a better vertical resolution.

The paper is organized as follows: Section 2 is devoted to a short description of the observations used in this work, as well as to the arguments used for latitude selection. Section 3 covers the radiative transfer model, including the description for the model atmosphere and its main parameters. The main results are shown in Section 4, first presenting the retrieved particle phase function for each latitude, then describing the vertical cloud structure as a function of latitude. A discussion on the meaning of the particle phase function can be found in Section 5, as well as the dynamical implications of the retrieved distribution of particles. A summary of the main conclusions of this work is presented in Section 6.

2. Observations

2.1. Overview of the observations

The observations used in this work are summarized in Table 1. In this table, we show the date of each observing run together with the sub-spacecraft planetocentric latitude B (close to the Equator for all cases), the sub-solar planetocentric latitude B' (ranging from 7°N to 12°N) and phase angle α, defined as explained above as the observer–planet–Sun angle (Sánchez-Lavega, 2011b). There are 72 images taken in later 2010 and 2011 in a blue wide filter (BL1, 451 nm) and three near infrared filters (Porco, 2004) which cover an intermediate methane band (MT2, 727 nm), its adjacent continuum (CB2, 752 nm) and a deep methane band (MT3, 890 nm). The prime criterion for the image selection was to cover a wide range of phase angles for a time short enough not to display evident changes in the apparent reflectivity of the planet, more than those derived from the changing geometry, as it will be discussed in Section 2.2. This proved to be a challenge, particularly in terms of latitude coverage, but 2011 offered a good sampling for the above mentioned filters for the Northern hemisphere. In the Equatorial Zone (latitudes below 20°N) the phase angle covers from ∼10° in August 2011 to ∼160° in March 2011, which gives access to scattering angles from ∼20° to ∼170°. Mid- and sub-polar latitudes, however, were not observed at this extreme phase angles and only reach ∼110°, therefore ∼70° scattering angles. The same is true for BL1 observations, not including all phase angles. Figs. 1 and 2 show cylindrically projected observations for all 18 dates in the three filters used here.

Table 1
Summary of the Cassini ISS observations.

Date	B	B'	α
2010-12-05	−0.02	7.21	80.2
2010-12-23	−0.02	7.46	60.8
2010-12-24	−0.03	7.48	71.2
2011-01-06	−0.07	7.66	113.3
2011-01-09	−0.07	7.71	146.9
2011-01-15	0.26	7.80	78.0
2011-01-21	0.31	7.88	95.4
2011-03-07	0.37	8.52	84.8
2011-03-19	0.17	8.69	157.7
2011-04-22	0.29	9.16	57.6
2011-05-03	0.37	9.31	86.3
2011-06-14	0.38	9.90	94.8
2011-07-14	0.10	10.31	20.5
2011-08-03	0.03	10.58	12.1
2011-08-06	0.16	10.63	28.2
2011-09-06	0.30	11.05	53.6
2011-11-30	0.20	12.18	41.8
2011-12-31	−0.79	12.58	79.4

B: sub-spacecraft planetocentric latitude; B': sub-solar planetocentric latitude; and α: phase angle.

It must be noted that, in December 2010, a GWS erupted in Saturn's mid-latitudes (Fischer, 2011; Sánchez-Lavega, 2011a), producing an intense disturbance of the atmosphere in a band roughly covering from 15°N to 40°N (Sánchez-Lavega et al., 2012; Sayanagi et al., 2013). For an analysis of the cloud structure of this phenomenon see Sanz-Requena et al. (2012) and Sromovsky et al. (2013). Obviously, those latitudes were not selectable for this research and there was a need for checking that the disturbance had not affected other latitudes.

One interesting point for the selected near infrared wavelengths is that they are close enough not to expect significant variations in the optical properties (e.g. single scattering albedos, real and imaginary refractive indices and phase functions), assuming that the spectral behavior is smooth. So our first assumption is that particle properties must be constant over the 727–890 nm wavelength range. However, methane absorption varies strongly from one wavelength to another, thus probing a good range of altitudes in the upper troposphere. The exact sounding levels depend strongly on the vertical distribution of particles, but for a clear atmosphere they can be calculated to be between 60 mbar (MT3) down to almost 6 bar (CB2), as shown by Roman et al. (2013). Since the role of particles is about the same for all the infrared wavelengths, in a cloudy atmosphere the sounding levels will move upwards and will tend to squeeze the weighting